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CATALYST COMPOSITION AND USE THEREOF IN ETHANE OXIDATION

REACTIONS

The present invention relates to a catalyst composition for the oxidation of ethane, and optionally ethylene, to acetic acid and ethylene, and to a process for the production of acetic acid and ethylene utilizing the aforesaid catalyst composition.

Catalyst compositions comprising molybdenum, vanadium and niobium in
5 combination with oxygen for use in processes for the production of acetic acid by the oxidation of ethane and/or ethylene are known in the art from, for example, US 4,250,346, EP-A-1043064, WO 99/20592 and DE 196 30 832.

US Patent No. 4,250,346 discloses the oxidative dehydrogenation of ethane to ethylene and acetic acid in a gas phase reaction, at a temperature of less than about
10 550°C using as a catalyst a composition comprising the elements molybdenum, X and Y in the ratio $\text{Mo}_a\text{X}_b\text{Y}_c$ wherein X is Cr, Mn, Nb, Ta, Ti, V and/or W, and preferably Mn, Nb, V and/or W; Y is Bi, Ce, Co, Cu, Fe, K, Mg, Ni, P, Pb, Sb, Si, Sn, Tl and/or U, and preferably Sb, Ce and/or U, a is 1, b is 0.05 to 1.0 and c is 0 to 2, and preferably 0.05 to 1.0, with the proviso that the total value of c for Co, Ni and/or Fe is less than 0.5.

15 WO 99/20592 relates to a method of selectively producing acetic acid from ethane, ethylene or mixtures thereof and oxygen at high temperature in the presence of a catalyst composition having the formula $\text{Mo}_a\text{Pd}_b\text{X}_c\text{Y}_d$ wherein X represents one or several of Cr, Mn, Nb, Ta, Ti, V, Te and W; Y represents one or several of B, Al, Ga, In, Pt, Zn, Cd, Bi, Ce, Co, Rh, Ir, Cu, Ag, Au, Fe, Ru, Os, K, Rb, Cs, Mg, Ca, Sr, Ba,
20 Nb, Zr, Hf, Ni, P, Pb, Sb, Si, Sn, Tl and U and $a=1$, $b=0.0001$ to 0.01 , $c=0.4$ to 1 and $d=0.005$ to 1 .

German patent application DE 196 30 832 A1 relates to a similar catalyst composition in which $a=1$, $b>0$, $c>0$ and $d=0$ to 2 . Preferably, $a=1$, $b=0.0001$ to

0.5, $c = 0.1$ to 1.0 and $d = 0$ to 1.0 .

The catalyst compositions of both WO 99/20592 and DE 19630832 require the presence of palladium.

EP-A-1043064 discloses a catalyst composition for the oxidation of ethane to ethylene and/or acetic acid and/or for the oxidation of ethylene to acetic acid which comprises in combination with oxygen the elements molybdenum, vanadium, niobium and gold in the absence of palladium according to the empirical formula :



wherein Y is one or more elements selected from the group consisting of: Cr, Mn, Ta,

10 Ti, B, Al, Ga, In, Pt, Zn, Cd, Bi, Ce, Co, Rh, Ir, Cu, Ag, Fe, Ru, Os, K, Rb, Cs, Mg, Ca, Sr, Ba, Zr, Hf, Ni, P, Pb, Sb, Si, Sn, Tl, U, Re, Te and La; a, b, c, d, e and f represent the gram atom ratios of the elements such that: $0 < a \leq 1$; $0 \leq b < 1$ and $a + b = 1$; $10^{-5} < c \leq 0.02$; $0 < d \leq 2$; $0 < e \leq 1$; and $0 \leq f \leq 2$.

WO 03/033138 discloses a catalyst composition for the selective oxidation of ethane to acetic acid and/or for the selective oxidation of ethylene to acetic acid which composition comprises in combination with oxygen the elements molybdenum, vanadium, niobium and gold in the absence of palladium according to the empirical formula: $\text{Mo}_a\text{W}_b\text{Au}_c\text{V}_d\text{Nb}_e\text{Z}_f$ (I)

20 wherein Z is one or more elements selected from the group consisting of: B, Al, Ga, In, Ge, Sn, Pb, Sb, Cu, Pt, Ag, Fe and Re; a, b, c, d, e and f represent the gram atom ratios of the elements such that: $0 < a \leq 1$; $0 \leq b < 1$ and $a + b = 1$; $10^{-5} < c \leq 0.02$; $0 < d \leq 2$; $0 < e \leq 1$; and $0.0001 \leq f \leq 0.05$. Preferably, Z is Sn. Said catalysts give high selectivity to acetic acid in combination with low, if any, selectivity to ethylene.

Acetic acid may be reacted with ethylene, in the presence of oxygen, to produce vinyl acetate. In particular, it is desirable to provide an integrated process for vinyl acetate production comprising a first step for the production of acetic acid and ethylene from ethane, and optionally ethylene, followed by subsequent reaction of said acetic acid and ethylene to produce vinyl acetate. Ideally the molar ratio of ethylene to acetic acid produced in the first step is approximately 1 : 1.

30 WO 01/90042 and WO 01/90043 both disclose an integrated process for the production of vinyl acetate, the first step of which is the oxidation of ethane to acetic acid and ethylene, with subsequent conversion of the acetic acid and ethylene to vinyl acetate.

EP-A-0 877 727 discloses an integrated process for the production of acetic acid and/or vinyl acetate in any pre-determined and variable proportions from a gaseous feedstock comprising ethylene and/or ethane. The integrated process comprises a first step wherein ethylene and/or ethane is catalytically oxidized in a first reaction zone to produce a first product stream comprising acetic acid, water and ethylene and optionally ethane, carbon monoxide and/or carbon dioxide. The acetic acid and ethylene produced in this first reaction zone are then contacted in a second reaction zone with a molecular oxygen-containing gas in the presence of a catalyst to produce a second product stream comprising vinyl acetate, water, acetic acid and optionally ethylene.

There remains a need to develop a catalyst composition for the oxidation of ethane, and optionally ethylene, to acetic acid and ethylene with high overall selectivity to acetic acid and ethylene and a reduced molar ratio of ethylene to acetic acid.

Surprisingly, it has now been found that by using a catalyst composition comprising molybdenum, vanadium, niobium in combination with oxygen, supported on a suitable support, and wherein said catalyst composition further comprises a component Z, which is one or more metals of Group 14 of the Periodic Table of the Elements, i.e. Ge, Sn and Pb, ethane, and optionally ethylene, may be oxidized to acetic acid and ethylene with high overall selectivity to acetic acid and ethylene.

Advantageously, it has been found that by using the catalyst composition of the present invention the ratio of acetic acid and ethylene produced may be approximately 1:1, the preferred ratio for subsequent reaction with oxygen to produce vinyl acetate. Furthermore, high overall selectivity may be achieved in the substantial absence of noble metals such as gold and/or palladium in the catalyst composition.

Accordingly, in a first aspect, the present invention provides a catalyst composition for the oxidation of ethane, and optionally ethylene, to acetic acid and ethylene, which catalyst composition comprises (i) a support, and (ii), in combination with oxygen, the elements molybdenum, vanadium and niobium, optionally tungsten and a component Z, which is one or more metals of Group 14 of the Periodic Table of Elements; wherein a, b, c, d and e represent the gram atom ratios of the elements Mo, W, Z, V and Nb respectively, such that :

$$0 < a \leq 1; 0 \leq b < 1 \text{ and } a + b = 1;$$

$$0.05 < c \leq 2;$$

$$0 < d \leq 2; \text{ and}$$

$$0 < e \leq 1.$$

Preferably $a > 0.01$, such as $a = 1$. Preferably $c \geq 0.1$. Preferably, $d \geq 0.1$, such as $0.1 \leq d \leq 0.5$. Preferably, $e > 0.01$. Preferably, $e \leq 0.6$, such as $0.01 \leq e \leq 0.6$.

The catalyst compositions according to the present invention may optionally
5 comprise a further component, Y, which is one or more elements selected from the group consisting of: Cr, Mn, Ta, B, Al, Ga, In, Pt, Zn, Cd, Bi, Ce, Co, Rh, Ir, Cu, Ag, Fe, Ru, Os, K, Rb, Cs, Mg, Ca, Sr, Ba, Ni, P, Sb, Si, Tl, U, Re, Te, La, Ti, Zr, Hf, Au and Pd.

Y may be present at a gram atom ratio, f, wherein $0 \leq f \leq 2$. Preferably, $f \geq 0.01$.
10 Preferably, $f \leq 0.5$, such as $0.01 \leq f \leq 0.5$.

More preferably, the catalyst compositions according to the present invention are substantially devoid of noble metals, such as gold and palladium.

Most preferably, Y, when present, is selected from the group consisting of Bi, Ca, Ce, Cu, K, P, Sb, La, Ti, Zr, Hf and Te and is most preferably selected from Ti and
15 Zr.

The catalyst composition of the present invention comprises a support. The support may be a non-oxide support, such as silicon carbide or graphite, but is preferably selected from one or more metal oxide supports, such as silica, titania, titanosilicates, alumina, aluminosilicates, zirconia or combinations thereof, such as a
20 mixture of silica and titania. Preferred supports include silica, titania and mixtures of titania and silica supports.

Certain elements, such as aluminium, titanium and zirconium, may be present in the catalyst composition of the present invention as a component of the support and/or as component Y.

25 The catalyst composition of the present invention comprises a component, Z, which is one or more of Ge, Sn and Pb. Preferably Z is Sn. Advantageously, it has been found that the addition of component Z at the gram atom ratios according to the present invention, alters the ratio of ethylene to acetic acid produced compared to an equivalent catalyst composition without component Z. The addition of component Z reduces the
30 ratio of ethylene to acetic acid produced whilst retaining high overall selectivity to ethylene and acetic acid. Thus, by using the catalyst compositions of the present invention, it is possible to produce a product stream comprising ethylene and acetic acid in an approximately 1:1 ratio, which may be subsequently used, without the need for the

further addition of ethylene and acetic acid, in the production of vinyl acetate. By “approximately 1:1”, as used herein, is meant a product stream in which the ratio of acetic acid to ethylene is between 0.8:1 and 1.2:1, preferably between 0.9:1 and 1.1:1.

A second aspect of the present invention relates to a process for the preparation of a catalyst composition according to the first aspect of the present invention, comprising the steps of:

- (a) forming a mixture comprising molybdenum, vanadium, niobium, a support material or a precursor thereof, component Z, and optionally tungsten in a solution;
- (b) drying the mixture to form a dried solid material; and
- (c) calcining the dried solid material to form the catalyst composition.

The mixture comprising molybdenum, vanadium, niobium, a support material or a precursor thereof, component Z, and optionally tungsten in a solution formed in step (a) of the second aspect of the present invention may also comprise a further component, Y, as previously defined, where this is a component of the catalyst composition.

Suitably the mixture comprising molybdenum, vanadium, niobium, support material, or a precursor thereof, component Z, optionally tungsten and optionally component Y may be formed by mixing compounds and/or complexes of each of the metals with the support material or precursor thereof in a suitable solvent. The solvent is preferably water. Most preferably the mixture is a solution in water having a pH in the range from 1 to 12, preferably from 2 to 8, at a temperature of from 20° to 100°C.

Preferably, the molybdenum is introduced in to the mixture in the form of ammonium salts such as ammonium heptamolybdate, or organic acids of molybdenum, such as acetates and oxalates. Other compounds of molybdenum which may be used include, for example, molybdenum oxides, molybdic acid and/or molybdenum chlorides.

Preferably, the vanadium is introduced in to the mixture in the form of ammonium salts, such as ammonium metavanadate or ammonium decavanadate, or organic acids of vanadium, such as acetates and oxalates. Other compounds of vanadium which may be used include, for example, as vanadium oxides and sulphates.

Preferably, the niobium is introduced in to the mixture in the form of ammonium salts, such as ammonium niobium oxalate. Other compounds of niobium, such as

niobium chlorides, may also be used, preferably complexed with an oxalate, a carboxylic acid or similar coordinating compound to improve solubility.

The support material may be introduced to the mixture of the metal components as a preformed support material, such as, for example, as silica. Supports comprising
5 two or more different support materials, for example, a mixture of titania and silica, may be introduced as a mixture of pre-formed support materials, such as pre-formed titania and pre-formed silica support materials. Alternatively, at least one of the support materials is introduced in the form of a suitable precursor thereof, for example, the silica may be introduced in the form of a silica sol or a silica-titania support may be
10 introduced in the form of a SiTi co-gel. Suitable SiTi co-gels include SiTi 4150 co-gel produced by Davicat (Grace-Davison).

Preferably, component Z is introduced in to the mixture in the form of an acetate, oxide, alkoxide or oxalate salt. Other compounds of component Z which may be used include, for example, halides and ammonium salts of Z. For example, preferred
15 tin compounds include tin (II) oxalate and ammonium hexafluorostannate. Most preferably, tin, where used, is introduced into the mixture in the form of a SnO₂ sol, stabilized with tetramethylammonium hydroxide.

Generally, in step (a) of the second aspect of the invention, the mixture of compounds containing the elements is prepared by dissolving sufficient quantities of
20 soluble metal compounds and dispersing any insoluble compounds so as to provide a desired gram-atom ratio of the elements in the catalyst composition. The support material or precursor thereof may be introduced at any suitable stage during mixing, but is preferably introduced after the preparation of a mixture of the molybdenum, vanadium, niobium, component Z, optional tungsten and optional component Y.

25 The solvent is then removed from the mixture by drying, preferably by spray-drying, to form a dried solid material. This dried solid material is then calcined to form the catalyst composition. Calcination is preferably performed by heating to a temperature of from 200 to 550°C, suitably in air or oxygen, for a period of from 1 minute to 24 hours.

30 The support typically comprises at least about 20% and/or up to about 90% by weight of the total weight of the catalyst composition. Preferably the support comprises at least 40wt% of the total weight of the catalyst composition and/or up to 60wt% of the total weight of the catalyst composition.

In a third aspect of the present invention there is provided a process for the production of acetic acid and ethylene from a gaseous mixture comprising ethane, and optionally ethylene, which process comprises contacting the gaseous mixture with a molecular oxygen-containing gas at elevated temperature in the presence of a catalyst composition as hereinbefore described.

Ethane and the optional ethylene may each be used in substantially pure form or admixed with one or more of nitrogen, methane, carbon dioxide and water in the form of steam, which may be present in major amounts, for example greater than 5 volume percent or one or more of hydrogen, carbon monoxide, C₃/C₄ alkanes and alkenes, which may be present in minor amounts, for example less than 5 volume percent.

The molecular oxygen-containing gas may be air or a gas richer or poorer in molecular oxygen than air, for example oxygen. A suitable gas may be, for example, oxygen diluted with a suitable diluent, for example nitrogen.

It is preferred to feed, in addition to ethane, optional ethylene and the molecular oxygen-containing gas, water (steam) because this can improve the selectivity to acetic acid.

The elevated temperature may suitably be in the range from 200 to 500°C, preferably from 200 to 400°C.

The pressure may suitably be atmospheric or superatmospheric, for example in the range from 1 to 50 bar, preferably from 1 to 30 bar.

The process of the third aspect may be a fixed bed or a fluidised bed process, preferably a fluidised bed process.

Operating conditions and other information applicable to the performance of the invention may be found in the aforesaid prior art, for example US Patent No. 4,250,346.

Typically, using the catalyst compositions of the present invention, the combined selectivity to acetic acid and ethylene is at least 70mol%, preferably at least 75 mol%, such as at least 80 mol%.

As used herein, selectivity refers to a percentage that reflects the amount of desired acetic acid product produced as compared to the total carbon in the products formed :-

$$\% \text{ selectivity} = 100 * \text{Moles of acetic acid produced} / S$$

wherein S = the molar acid-equivalent sum (carbon basis) of all carbon-containing products, excluding the alkane in the effluent.

In an integrated process for the production of vinyl acetate wherein the first step is the oxidation of ethane (optionally with ethylene), it is desired to produce acetic acid and ethylene from the ethane oxidation step at an approximate ratio of ethylene to acetic acid of 1:1 since this is the optimum ratio for subsequent reaction of acetic acid and ethylene with oxygen to produce vinyl acetate.

Hence, in a fourth aspect, the present invention provides an integrated process for the production of vinyl acetate from a gaseous mixture comprising ethane, and optionally ethylene, which process comprises:

(i) contacting, in a first reaction zone, a gaseous mixture comprising ethane, and optionally ethylene, with a molecular oxygen-containing gas at elevated temperature in the presence of a catalyst composition as hereinbefore described to produce a first product stream comprising acetic acid and ethylene, and
(ii) contacting, in a second reaction zone, at least a portion of said ethylene and at least a portion of said acetic acid from said first product stream with a molecular oxygen-containing gas at elevated temperature in the presence of a catalyst suitable for the production of vinyl acetate, to produce a second product stream comprising vinyl acetate.

The second reaction zone for the production of vinyl acetate may be a fixed bed reactor but is preferably a fluidised bed reactor.

The oxygen feed to the second reaction zone may be any suitable oxygen-containing gas, and may suitably be air or a gas richer or poorer in molecular oxygen than air. Suitably, the gas may be oxygen diluted with a suitable diluent, for example, nitrogen, argon or carbon dioxide. Preferably essentially pure oxygen is used as the oxygen feed.

The first product stream preferably comprises acetic acid and ethylene in an approximately 1:1 ratio.

In one embodiment the first product stream may be fed directly to the second reaction zone. In this embodiment, the ethylene and acetic acid are co-fed to the second reaction zone.

Alternatively, the first product stream may be treated, e.g. by conventional separation, to produce an ethylene-containing stream and an acetic acid containing stream from said product stream, and said ethylene and acetic acid containing streams may be fed separately to the second reaction zone. In particular, the ethylene-

containing stream may comprise ethylene in substantially pure form or may comprise ethylene as a mixture with one or more of nitrogen, methane, ethane, carbon dioxide and water in the form of steam or one or more of hydrogen, C₃/C₄ olefins or alkanes.

Where the second reaction zone is a fluidised bed reactor, the acetic acid may be introduced into the reactor in liquid form or in vapour form. Where the second reaction zone is a fixed bed reactor then the acetic acid is preferably introduced in to the reactor in vapour form.

The production of vinyl acetate in the second reaction zone, when carried out in a fluidised bed reactor, may suitably be operated at a temperature from 100 to 400°C, preferably 140 to 210°C and a pressure of 10⁵ to 2 x 10⁶ Pa gauge (1 to 20 barg), preferably 6 x 10⁵ to 1.5 x 10⁶ Pa gauge (6 to 15 barg), especially 7 x 10⁵ to 1.2 x 10⁶ Pa gauge (7 to 12 barg).

Catalysts known in the art for the production of vinyl acetate may be used in the second reaction zone. Thus, catalysts active for the production of vinyl acetate which may be used in a second reaction zone may comprise, for example, catalysts as described in GB 1 559 540; US 5,185,308 and EP-A-0672453 the contents of which are hereby incorporated by reference.

GB 1 559 540 describes a catalyst active for the preparation of vinyl acetate by the reaction of ethylene, acetic acid and oxygen, the catalyst consisting essentially of: (1) a catalyst support having a particle diameter of from 3 to 7 mm and a pore volume of from 0.2 to 1.5 ml/g, a 10% by weight water suspension of the catalyst support having a pH from 3.0 to 9.0, (2) a palladium-gold alloy distributed in a surface layer of the catalyst support, the surface layer extending less than 0.5 mm from the surface of the support, the palladium in the alloy being present in an amount of from 1.5 to 5.0 grams per litre of catalyst, and the gold being present in an amount of from 0.5 to 2.25 grams per litre of catalyst, and (3) from 5 to 60 grams per litre of catalyst of alkali metal acetate.

US 5,185,308 describes a shell impregnated catalyst active for the production of vinyl acetate from ethylene, acetic acid and an oxygen containing gas, the catalyst consisting essentially of: (1) a catalyst support having a particle diameter from about 3 to about 7 mm and a pore volume of 0.2 to 1.5 ml per gram, (2) palladium and gold distributed in the outermost 1.0 mm thick layer of the catalyst support particles, and (3) from about 3.5 to about 9.5% by weight of potassium acetate wherein the gold to

palladium weight ratio in said catalyst is in the range 0.6 to 1.25.

EP-A-0672453 describes palladium containing catalysts and their preparation for fluidised bed vinyl acetate processes.

Preferably, the catalyst suitable for the production of vinyl acetate comprises a
5 Group VIII metal, a catalyst promoter and an optional co-promoter. With regards to the Group VIII metal, the preferred metal is palladium. Suitable sources of palladium include palladium (II) chloride, sodium or potassium tetrachloropalladate, (II),
(Na_2PdCl_4 or K_2PdCl_4), palladium acetate, palladium (II) nitrate or palladium (II)
sulphate. The metal may be present in a concentration of greater than 0.2% by weight,
10 preferably greater than 0.5% by weight based upon total weight of catalyst. The metal concentration may be as high as 10% by weight.

In addition to the Group VIII metal, the catalyst suitable for the production of vinyl acetate may comprise a promoter. Suitable promoters include gold, copper, cerium or mixtures thereof. A preferred promoter is gold. Suitable sources of gold
15 include gold chloride, tetrachloroauric acid (HAuCl_4), NaAuCl_4 , KAuCl_4 , dimethyl gold acetate, barium acetoaurate or gold acetate. The preferred gold compound is HAuCl_4 . The promoter metal may be present in an amount of from 0.1 to 10% by weight in the finished catalyst.

The catalyst suitable for the production of vinyl acetate may also comprise a co-
20 promoter material. Suitable co-promoters include Group I, Group II, lanthanide or transition metals, for example cadmium, barium, potassium, sodium, manganese, antimony, and/or lanthanum, which are present in the finished catalyst as salts, e.g. an acetate salt. The preferred salts are potassium or sodium acetate. The co-promoter is preferably present in the catalyst composition in a concentration of 0.1 to 15% by
25 weight of catalyst, more preferably, from 1 to 5% by weight.

Where a liquid acetic acid feed is used the preferred concentration of co-promoter salt is up to 6% by weight, especially 2.5 to 5.5%. Where the acid is introduced in the vapour phase the co-promoter salt is preferably present in a concentration up to 11 wt%.

30 The catalyst suitable for the production of vinyl acetate may be a supported catalyst. Suitable catalyst supports include porous silica, alumina, silica/alumina, titania, silica/titania or zirconia. In particular for use in a fluidised bed process, the support is preferably silica, and, suitably, the support may have a pore volume from 0.2

to 3.5 mL per gram of support, a surface area of 5 to 800 m² per gram of support and an apparent bulk density of 0.3 to 1.5 g/mL.

The catalyst suitable for the production of vinyl acetate may be prepared by any suitable method. For example the catalyst for the production of vinyl acetate may be prepared by the method detailed in EP-A-0672453.

Advantageously, in the fourth aspect of the present invention, high concentrations of ethylene are fed to the second reaction zone. High concentrations of ethylene (greater than 50 mol% of the total feed) fed to the second reaction zone maximize the selectivity to vinyl acetate.

Desirably, the concentration of ethylene fed to the second reaction zone is at least 50 mol % of the total feed to the second reaction zone, preferably, at least 55 mol%, more preferably at least 60 mol%. Suitably, the concentration of ethylene is up to 85 mol% of the total feed to the second reaction zone, preferably, in the range at least 50 mol% to 80 mol%, such as at least 55 mol% to 80 mol%.

Production of vinyl acetate by reaction of ethylene, acetic acid and oxygen in which the combined feed to the vinyl acetate reaction comprises at least 60 mol% is described in EP 0985 657 A1, the contents of which are herein incorporated by reference.

A ratio of ethylene to acetic acid of approximately 1:1 is also the optimum ratio for an integrated process for the production of ethyl acetate.

Thus, the catalyst composition of the present invention may also be utilized in an integrated process for the production of ethyl acetate.

Hence, in a fifth aspect, the present invention provides an integrated process for the production of ethyl acetate from a gaseous mixture comprising ethane, and optionally ethylene, which process comprises:

(i) contacting, in a first reaction zone; a gaseous mixture comprising ethane, and optionally ethylene, with a molecular oxygen-containing gas at elevated temperature in the presence of a catalyst composition as hereinbefore described to produce a first product stream comprising acetic acid and ethylene, and

(ii) contacting, in a second reaction zone, at least a portion of said ethylene and at least a portion of said acetic acid from said first product stream, and optionally water, at elevated temperature in the presence of a catalyst suitable for the production of ethyl acetate, to produce a second product stream comprising ethyl acetate.

The second reaction zone for the production of ethyl acetate may be a fixed bed reactor but is preferably a fluidised bed reactor.

The first product stream preferably comprises acetic acid and ethylene in an approximately 1:1 ratio.

5 In one embodiment the first product stream may be fed directly to the second reaction zone. In this embodiment, the ethylene and acetic acid are co-fed to the second reaction zone.

Alternatively, the first product stream may be treated, e.g. by conventional separation, to produce an ethylene-containing stream and an acetic acid containing
10 stream from said first product stream, and said ethylene and acetic acid containing streams may be fed separately to the second reaction zone. In particular, the ethylene-containing stream may comprise ethylene in substantially pure form or may comprise ethylene as a mixture with one or more of nitrogen, methane, ethane, carbon dioxide and water in the form of steam or one or more of hydrogen, C₃/C₄ olefins or alkanes.

15 Preferably, in the fifth aspect of the present invention, the concentration of ethylene fed to the second reaction zone is at least 50 mol % of the total feed to the second reaction zone, preferably, at least 55 mol%, more preferably at least 60 mol%.

Catalysts known in the art for the production of ethyl acetate may be used in the fifth aspect of the process of the present invention. Catalysts active for the production
20 of ethyl acetate which may be used in the second reaction zone may comprise, for example, catalysts as described in EP-A-0926126, the contents of which are hereby incorporated by reference.

EP-A-0926126 describes a process for the production of esters by reacting, in a plurality of reactors set up in series, ethylene, propylene or mixtures thereof with a
25 saturated aliphatic C₁-C₄ mono-carboxylic acid in the presence of a heteropolyacid catalyst.

The present invention will now be further illustrated by reference to the following Examples.

CATALYST PREPARATION

30 Comparative Catalyst A

Mo_{1.00}V_{0.529}Nb_{0.124}O_x (=Mo_{60.5}V₃₂Nb_{7.5}O_x) on silica

The following three solutions were prepared:

Solution A: 214 g of ammonium heptamolybdate was dissolved in 250 g of water at

45°C with stirring.

Solution B: 75 g of ammonium metavanadate was added to 725 g of water in a 2-liter beaker and heated to 80°C. The ammonium metavanadate did not completely dissolve.

5 Solution C: 74 g of ammonium niobium oxalate was added to 275 g of water in a 6-liter stainless steel beaker and heated to 45°C. A sol formed within 30 minutes.

Solution C was added to solution B and allowed to digest at 80°C for 30 minutes. Solution A was then added to the mixture, which was then stirred for 15 minutes at medium heat.

10 638 grams of silica sol (Nalco 41D01) was then added to the stirred mixture.

The slurry was homogenized at 10,000 rpm for approximately 2 minutes. Spray drying was done in a mini-Niro spray-drier immediately after the solution was homogenized. Spray drying conditions were as follows: an inlet temperature of 290°C inlet and an outlet temperature of 138°C.

15 The catalyst composition was calcined in air for 3 hours at 375°C in a static muffle furnace before use.

The resulting spray-dried catalyst composition has a nominal composition $\text{Mo}_{60.5}\text{V}_{32}\text{Nb}_{7.5}\text{O}_x$ on silica, and at a nominal metal loading of 50% of the total catalyst weight.

20 **Catalyst B**

Catalyst B has a similar nominal composition as Comparative Catalyst A, but with the further addition of tin at a gram atom ratio of 0.33.

The catalyst composition was prepared as described for Catalyst A, but SnO_2 sol, stabilized with tetramethylammonium hydroxide was used as the tin source.

25 **Catalyst C**

Catalyst C has a similar nominal composition as Catalyst B, except that approximately half of the tin was replaced by titanium, to give a catalyst with a nominal composition comprising tin and titanium each at a gram atom ratio of 0.165.

30 The catalyst composition was prepared as described for Catalyst A, but SnO_2 sol, stabilized with tetramethylammonium hydroxide was used as the tin source and titanium isopropoxide was used as the titanium source.

Catalyst D

Catalyst D has a similar nominal composition as Catalyst B, but was supported

on a silica-titania support.

The catalyst composition was prepared as described for Catalyst B, except that SiTi 4150, a co-gel supplied by Davison, was used as the support in place of the silica sol used in Catalyst B.

5 Catalyst E

Catalyst E has a similar nominal composition as Catalyst D, but was supported on a mixture of silica and silica-titania supports.

The catalyst composition was prepared as described for Catalyst B, except that SiTi 4150, a co-gel supplied by Davison and Nalco 41D01, silica sol, in a 50:50 ratio
10 were used as support materials.

Comparative Catalyst F

Catalyst F has a similar nominal composition as Catalyst A, but with the further addition of Ti at a gram atom ratio of 0.33.

The catalyst composition was prepared as described for Catalyst A, but titanium
15 isopropoxide was used as the titanium source.

CATALYST TESTING

The catalyst compositions were tested in a fluidised bed reactor under the conditions indicated for each catalyst in the Tables below.

(HOS = Hours on stream, Sel = selectivity, STY = Space-Time Yield, Conv =
20 conversion, Acetic = acetic acid, e/a = ethylene/acetic acid ratio)

The catalyst to be used for testing was sieved to obtain a specific particle size distribution (psd) of 70% 230/325 mesh (50/50), 25% pans (fines) and 5% greater than 170 mesh.

The catalyst (10g) and an inert diluent with the same particle size distribution (St Gobain SA 539 alpha alumina, 43g, density 1.27g/ml) were added into a 40 cc fluidised
25 bed reactor.

The reactions were typically performed at temperatures between 280°C and 320°C and at a reaction pressure of 16 barg. Ethane, ethylene (to mimic a recycle of ethylene), nitrogen and oxygen mixture was fed to the reactor using Brooks Mass Flow
30 Controllers. Water was added by vaporisation and mixing with these feed gases prior to the reaction zone.

The volatile reactor effluent was sampled and analyzed by gas liquid chromatography whereas water and acetic acid were condensed and analyzed by gas

liquid chromatography. The reactor bed temperature was monitored by a moving thermocouple.

Comparative Catalyst A

Run Conditions (Feed mol %)

HOS	Max T	Total Flow	GHSV	C ₂ H ₆	C ₂ H ₄	H ₂ O	O ₂	N ₂
	°C	ml/min	h ⁻¹					
1-22	289	462	3200	60.0	5.0	5.0	6.5	23.5
24-48	302	462	3200	60.0	5.0	5.0	6.5	23.5
49-70	311	462	3200	60.0	5.0	5.0	6.5	23.5
71-92	317	462	3200	60.0	5.0	5.0	6.5	23.5

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Results

HOS	Max T	Sel			STY			Conv %		e/a
Avg	°C	C ₂ H ₄	Acetic	CO _x	C ₂ H ₄	Acetic	CO _x	C ₂ H ₆	O ₂	
		%	%	%						
1-22	289	62	29	10	54	53	21	5	48	2.2
24-48	302	61	30	10	77	81	30	7	68	2.1
49-70	311	60	30	10	98	105	40	8	85	2.0
71-92	317	60	29	10	107	111	4	9	93	2.1

These results show that the Comparative Catalyst A, which contains no component Z, produces ethylene and acetic acid with good overall selectivity, but at a high ratio of ethylene to acetic acid (e/a) of approximately 2:1.

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Catalyst B

Run Conditions (Feed mol %)

HOS	Max T	Total Flow	GHSV	C ₂ H ₆	C ₂ H ₄	H ₂ O	O ₂	N ₂
	°C	ml/min	h ⁻¹					
1-24	295	462	3200	60.0	5.0	5.0	6.5	23.5
25-47	309	462	3200	60.0	5.0	5.0	6.5	23.5
49-70	280	462	3200	60.0	5.0	5.0	6.5	23.5

Results

HOS	Max T	Sel			STY			Conv %		e/a
Avg	°C	C ₂ H ₄	Acetic	CO _x	C ₂ H ₄	Acetic	CO _x	C ₂ H ₆	O ₂	
		%	%	%						
1-24	295	40	42	18	37	83	39	6	76	1.0
25-47	309	42	40	18	49	102	52	7	95	1.0
49-70	280	41	43	16	27	60	24	4	49	1.0

These results show that the Catalyst B, which contains tin as component Z, produces ethylene and acetic acid with good overall selectivity and at a ratio of ethylene to acetic acid of approximately 1:1. Hence, addition of Sn to the catalyst composition has allowed the ratio of ethylene to acetic acid to be reduced, whilst maintaining high overall selectivity, compared to the Comparative Catalyst A.

Catalyst C

10 Run Conditions (Feed mol %)

HOS	Max T	Total Flow	GHSV	C ₂ H ₆	C ₂ H ₄	H ₂ O	O ₂	N ₂
	°C	ml/min	h ⁻¹					
2-29	277	462	3200	60.0	5.0	5.0	6.5	23.5
30-51	296	462	3200	60.0	5.0	5.0	6.5	23.5
53-73	325	462	3200	60.0	5.0	5.0	6.5	23.5

Results

HOS	Max T	Sel			STY			Conv %		e/a
Avg	°C	C ₂ H ₄	Acetic	CO _x	C ₂ H ₄	Acetic	CO _x	C ₂ H ₆	O ₂	
		%	%	%						
2-29	277	42	42	16	21	45	18	3	34	1.0
30-51	296	43	39	19	36	70	35	5	57	1.1
53-73	325	40	39	21	50	102	63	7	93	1.0

These results show that the Catalyst C, which contains tin as component Z and titanium as a component Y, produces ethylene and acetic acid with good overall selectivity and at a ratio of ethylene to acetic acid of approximately 1:1. Hence, addition of Sn and Ti to the catalyst composition has allowed the ratio of ethylene to acetic acid to be reduced, whilst maintaining high overall selectivity, compared to the Comparative Catalyst A.

Catalyst D

Run Conditions (Feed mol %)

HOS	Max T	Total Flow	GHSV	C ₂ H ₆	C ₂ H ₄	H ₂ O	O ₂	N ₂
	°C	ml/min	h ⁻¹					
15	285	432	3190	59.5	5.0	4.9	6.3	24.3
19-21	297	432	3190	59.5	5.0	4.9	6.3	24.3
25-37	315	432	3190	59.5	5.0	4.9	6.3	24.3

10 Results

HOS	Max T	Sel			STY			Conv %		e/a
Avg	°C	C ₂ H ₄	Acetic	CO _x	C ₂ H ₄	Acetic	CO _x	C ₂ H ₆	O ₂	
		%	%	%						
15	285	18	61	22	18	130	49	3	45	0.3
19-21	297	20	57	23	28	168	72	4	62	0.4
25-37	315	23	53	24	48	234	114	5	92	0.5

These results show that the Catalyst D, which contains tin as component Z and Ti as part of the support, produces ethylene and acetic acid with good overall selectivity but at a ratio of ethylene to acetic acid of less than 1:1. Hence, addition of Sn and Ti to the catalyst composition has allowed the ratio of ethylene to acetic acid to be reduced, whilst maintaining high overall selectivity, compared to the Comparative Catalyst A.

Catalyst E

Run Conditions (Feed mol %)

HOS	Max T	Total Flow	GHSV	C ₂ H ₆	C ₂ H ₄	H ₂ O	O ₂	N ₂
	°C	ml/min	h ⁻¹					
2-24	293	463	3190	60.0	5.1	4.9	6.7	23.3
25-45	315	463	3190	60.0	5.1	4.9	6.7	23.3

Results

HOS	Max T	Sel			STY			Conv %		e/a
Avg	°C	C ₂ H ₄	Acetic	CO _x	C ₂ H ₄	Acetic	CO _x	C ₂ H ₆	O ₂	
		%	%	%						
2-24	293	28	51	21	25	96	43	4	68	0.5
25-45	315	32	47	21	42	130	67	6	99	0.7

- These results show that the Catalyst E, which contains tin as component Z and Ti as part of the support, produces ethylene and acetic acid with good overall selectivity but at a ratio of ethylene to acetic acid of less than 1:1. Hence, addition of Sn and Ti to the catalyst composition has allowed the ratio of ethylene to acetic acid to be reduced, whilst maintaining high overall selectivity, compared to the Comparative Catalyst A.

Catalyst F

10 Run Conditions (Feed mol %)

HOS	Max T	Total Flow	GHSV	C ₂ H ₆	C ₂ H ₄	H ₂ O	O ₂	N ₂
	°C	ml/min	h ⁻¹					
0-194	310-320	428	3200	60.2	5.0	5.0	6.5	23.3

Results

HOS	Max T	Sel			STY			Conv %		e/a
Avg	°C	C ₂ H ₄	Acetic	CO _x	C ₂ H ₄	Acetic	CO _x	C ₂ H ₆	O ₂	
		%	%	%						
176-194	320	6	60	33	8	165	100	5	100	0.1

These results show that the Comparative Catalyst F, which contains titanium as a catalyst component but does not comprise a Group 14 metal produces predominantly acetic acid.

Comparison of Catalysts B, D and E shows that the addition of Ti as part of the support also influences the ratio of ethylene to acetic acid produced.

Comparison of Catalysts C, D and E with F shows that the addition of Sn and Ti mitigates the effect of Ti alone, allowing the ratio of ethylene to acetic acid to be tailored to approximately 1:1.

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